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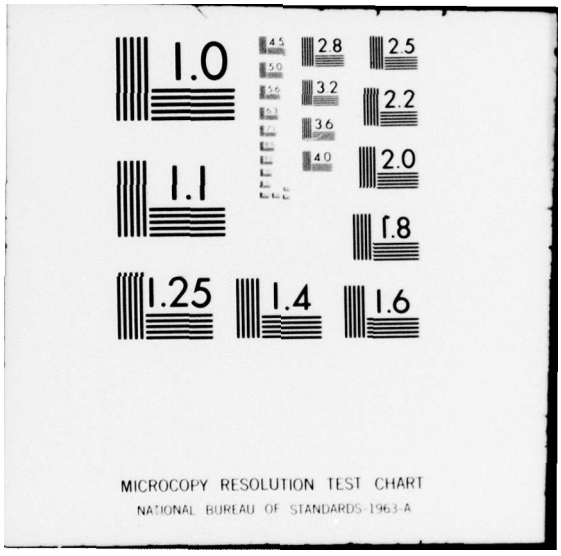
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THE RESEARCH AND DEVELOPMENT METHODS OF WILBUR AND ORVILLE WRIGHT

Malcolm L. Ritchie

August 1976

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In the process of solving the problems of powered flight by man, Wilbur and Orville Wright, put together in their own experience, the synthesis of engineering, science, and operational test which still characterizes aerospace research and development. They did it by themselves, becoming first engineers, then scientists, and finally test pilots.

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Foreword

There are three major sources of information for this paper. Most of the original material dealing directly with the history of aviation is in the Library of Congress. The two-volume publication edited by McFarland (4) contains most of this information. Helpful guidance to the Library of Congress was provided by Arthur G. Renstrom, who has prepared a highly useful chronology: Wilbur and Orville Wright: A Chronology. Washington: Library of Congress, 1975.

The second major source is the collection of the Personal Papers of Orville Wright, which his niece Ivonette Wright Miller has graciously made available by placing them in the Wright State University Archives.

The third major source is Paul Garber, Historian Emeritus of the Smithsonian Institution, who was present at the 1908 tests at Fort Myer, and who has lived most of the history of aviation.

While these information sources have been invaluable, the responsibility for the contents of this paper lie, of course, with the author.

I am indebted to the following for steady encouragement and assistance throughout the research and writing phase: Dr. Patrick Nolan of the Wright State University Archives, Nataraj S. Nataraj, John M. Howard, and Doris Havens.

I am indebted to Dr. Charles Hutchinson and Dr. Gordon Eckstrand of the U. S. Air Force for encouragement and for providing some financial assistance as a part of the work on Grant No. AFOSR 73 - 2569.

Summary

In the process of solving the problems of powered flight by man Wilbur and Orville Wright put together in their own experience the synthesis of engineering, science, and operational test which still characterizes aerospace research and development. They did it by themselves becoming first engineers, then scientists, and finally test pilots.

When Wilbur and Orville Wright addressed the problem of "manflight" in 1899, they were mechanically competent bicycle manufacturers with a good high school education. By July 1901 they were publishing articles in serious engineering journals. Their published articles show that they were masters of the current aeronautical engineering by late 1901. The notebooks and letters they did not publish show that by the end of 1901 they knew more about aerodynamics than anyone else ever had. More importantly, they knew enough to design a machine that could lift off with the power they could make available.

But they also knew that being aeronautical engineers and aerodynamic scientists was still not enough. They also had to become research test pilots before they could untangle those complex relations with the invisible wind that had overcome all their predecessors. They were barely proficient enough by the time their "flyer" could take them to dangerous heights.

Between May 30, 1899 and December 17, 1903 they not only taught themselves aeronautical engineering, aerodynamics, and test flying, they also designed and built a series of increasingly sophisticated machines: a controllable five foot biplane kite, three large gliders, three aerodynamic test machines, one airplane, a complete airplane control system, one engine, and two propellors (for which they had first to develop a propellor theory).

How they managed to accomplish these things in a period of just over 4.5 years is a story that deserves to be better understood than it is.

Algebra, Trigonometry, and Mechanics

In the Wright State University Library (Dayton, Ohio) there are copies of high school report cards for Wilbur for the years 1882, 3, 4, and 5, and for Orville for 1887, 8, and 9. Their grades were good but not outstanding - perhaps the 85 th to 90 th percentile in their classes. They both took substantial courses including algebra, geometry, and trigonometry. When in 1899 they would confront the serious literature of aeronautics, these courses would provide the mathematical skills

required to read and understand that literature.

The home in which they grew up was a modest one, but it had better than a modest supply of books. One of these was: E. J. Marey, "Animal Mechanism: A Treatise on Terrestrial and Aerial Locomotion"(1). This book was oriented toward measurement of and experiment on the means by which insects and birds fly. Many pictures show ingenious apparatuses for observing and measuring the movement of wings. For example, Marey notes that a bird's wing, at different points in its length,

> "...presents very remarkable changes of plane. At the inner parts of the body, the wing inclines considerably both downwards and backwards, while near its extremity, it is horizontal and sometimes slightly turned up." p. 210.

Marey described a table of data ascribed to the"Dutch Physiologist Hartings". This table related the weight of birds to the area of its wings. For a wide range of birds it showed a reasonably consistent proportion of the square root of the area to the cube root of the weight.

Marey closed his treatise by noting that many experimenters were studying bird flight, and that he himself had been

> "....sustained in this laborious analysis of the different acts in the flight of the bird, by the assured hope of being able to imitate, more or less imperfectly, this admirable type of aerial locomotion....The problem of aerial locomotion, formerly considered a Utopian scheme, is now approached in a truly scientific manner." p. 277

His plan was to continue in measurement and analysis of bird flight until he could imitate those movements faithfully.

It seems quite clear that both Wilbur and Orville had read Marey thoughtfully,

for each of them was to refer to it in later years in recounting the development of their concepts.

One of the well-known stories about the Wright home is that their father brought home a toy helicopter which they as boys flew around the house. The toy was called a "planaphore" by its inventor Penaud, but we would call it a toy airplane. It had a stick for a fuselage, a single wing mounted just behind the center of gravity, a horizontal tail, and a propellor driven by a rubber band. The horizontal tail was set with its leading edge slightly below its trailing edge. This toy airplane was stable and would fly reasonable distances.

What is not so well known about this toy airplane is that Wilbur and Orville reproduced it in varying sizes. They discovered that some very different things happened to the machine when it was simply scaled up to a larger size.

As Wilbur and Orville became young men they had developed skills at working with both wood and metal. Early they built the press that printed their newspaper. Later they built the one-cylinder gas engine which powered the tools in their bicycle factory. They would go on to design, build, test, and maintain every machine they used during their aviation research and development phase.

They began selling and servicing bicycles, then soon came to manufacture their own bicycles under the names "Wright" and "Van Cleve". The bicycle business was seasonal, and it was in the off season that they would make time for aeronautical experiments. The bicycle business provided all the money they used in aeronautical research.

They Taught Themselves Engineering

Their serious interest in aviation began with a review of the literature. On May 30, 1899 Wilbur wrote to the Smithsonian Institution stating that he intended to work on the problems of flying and would like to know what had been done before. The Smithsonian sent them some reports and sent them citations of other publications, which they purchased.

Both brothers would later express their amazement at the amount of information they discovered. They read publications by Langley, Mouillard, Chanute, Means, and others. Langley reported his experiments in aerodynamics and flight tests of his scale model powered aircraft (which he called "aerodromes"). Chanute had done a masterful survey of flying experiments before 1894, and he carefully analyzed what had been learned. Means assembled uncritically a collection of valuable and worthless information in three "Aeronautical Annuals" for the years 1895, 6, and 7. They discovered the British and French aeronautical journals, which brought them up to date and kept them current.

As they read that literature, discussed it thoroughly, and then began to experiment, they matured as aeronautical engineers. 26 months after the letter to the Smithsonian they would themselves be contributing to the literature (July 1901). In 32 months (Jan. 10, 1902) they would not only be the world's most competent aeronautical engineers, but would have put together the method that resulted in the 1903 flyer and which still characterizes aerospace technology today.

In July 1901 an article by Wilbur appeared in the Aeronautical Journal of London under the title, "Angle of Incidence". By angle of incidence he meant what we now call angle of attack - that angle between the airfoil chord line and the relative wind. The article was a clear exposition of the angular relations involved and posed a plea to his fellow investigators to be consistent in their terminology.

In that same month another article by Wilbur appeared in the German Illustrated Aeronautical Journal. It presented the advantages of the prone flying position for glider operations. This article has not received much attention from serious aviation historians, but there is a point in it which is worth considering. The argument was that the prone flying position reduced drag. The argument was quantitative and the drag due to the operator himself was reduced by about one third. Wilbur and Orville were serious about every source of drag. They knew their machine would have to be efficient to get off the ground at all with the kind of horsepower they would be able to muster.

In September 1901 Wilbur was in Chicago addressing the Western Society of

Engineers. That paper shows clearly that Wilbur and Orville were well ahead of everybody else in conceiving how to go about developing a flying machine. They did not use the word "airplane" or "aeroplane" to refer to a flying machine. To them the word in either form was a technical term. An aeroplane was a flat surface in dynamic contact with the air, which was to be distinguished from an aerocurve. Their unpowered machines they called gliders and all their powered machines they called "flyers".

After Wilbur returned from Chicago he joined Orville in making a series of laboratory tests of aerodynamic principles. When these tests were finished they knew how to proceed. Wilbur wrote to Chanute on January 10, 1902, "I think our experiments show conclusively that man can build wings superior to those of any bird in dynamic efficiency for soaring." They were then in a position to proceed directly toward the objective of powered flight.

Though their method was in place by the end of 1901 it would take two more years before they could carry all of it through to final first flight. It would be five years after that - 1908 before they would become famous. There is a reason, it seems, why fame was so long in coming, and why it finally came to them in France. That reason is that the French aviation enthusiasts knew enough to recognize the quality of the achievement the first time they saw Wilbur fly.

The French had the largest and most sophisticated group of aeronautical investigators in the world. For that reason it had been difficult for them to believe than anyone not in regular direct contact with their group was making revolutionary progress. They had heard about the Wright brothers, of course, but as a group remained entirely skeptical. But, to their everlasting credit, as soon as they saw Wilbur's graceful flight under positive control, they immediately pulled out all the stops in their praise and recognition. Only after they became famous in France were they famous in their own country, where only Octave Chanute was qualified to understand what they had done.

They Became Scientists of Necessity

When Wilbur and Orville began reading the serious aviation literature, it was immediately obvious to them that they had to make some decisions about it. They would later say that about 90% of it was garbage. They had to decide for themselves what was garbage and what was useful. After considerable deliberation they decided to adopt the approach of Lilienthal and Chanute - that is to build gliders as a means of solving problems of aerodynamics and control before trying to put motors on them. They said they wanted to learn how to fly and how to build machines that would fly before attempting powered flight.

Otto Lilienthal had built a series of gliders over a period of several years. He flew them himself, having constructed an artificial hill near his Berlin home to increase gliding time. But he was doing more than just learning to glide. He kept accurate records of wind, glide distance, weight carried, and time. These figures he related to airfoil shape and to lift and drag. By noting how shallow a glide he could get, he had an index of the lift and drag efficiency of the machine. The data from these flights were published and they formed the kind of information Wilbur and Orville could use as the basis for building gliders themselves and testing their own ideas. Lilienthal had been killed in one of his gliders in 1896.

Very much alive and living in Chicago was Octave Chanute. Though past retirement age, having been born in France in 1832, he continued vigorously as a disseminator of technical information about aviation. His book, "Progress in Flying Machines" was published in 1894 and recently republished (2). The book was so well done that one hardly needs to look elsewhere to study aviation before that date. It contained 85 pictures and drawings of flying machines and components, and noted that 56 of these had been subjected to experimental test. He summarized what had been learned and outlined the problems which must still be solved before "manflight" would be realized. He concluded that whoever would solve these problems must go into the air as Lilienthal had done. In an article in the "Aeronautical Annual" for 1897 he stated this position clearly:

"I further reached the conclusion that the seventh problem, the maintenance of the equilibrium under all circumstances, was by far the most important, and the first which should be solved....

"I therefore published an article....in which I advised those seeking a solution of the problem of flight to turn their attention to experiments in soaring flight, with full-sized apparatus carrying a man, as the quickest, cheapest, and surest way of ascertaining the exact conditions which must be met in practical flight.

This mode of procedure doubtless involves a certain amount of personal danger of accident. It might be pointed out that the advice is easy to give, but hazardous to follow, and so I further determined to try such experiments myself, sofar as my limited personal means would allow...." (3, pp. 31f).

Wilbur and Orville deliberately decided to follow the path of Lilienthal and Chanute. Wilbur had already said in the letter to the Smithsonian that "It is possible to fly without motors but not without knowledge and skill." In this discussion we will return to each of these terms. From the start they intended to build flying machines to develop their flying skill and then use their skilled experiences to help interpret and develop their machines. Personal flying was indispensable to the progress they made.

After they had analyzed the problems and decided to follow him, they criticized Lilienthal. They noted that Lilienthal was a failure in that he killed himself before he solved the problems of flight. He failed, they said, for two reasons. One of these was that his method did not allow him to gain enough skill. In the five years of his gliding flights he accumulated a total of only five hours in the air. Wilbur noted that five hours was inadequate for complex skills. No acrobat, he said, could perform even the simplest of his skilled feats with only five hours practice. Whoever would fly would have to provide a way to build up flying skill.

The other point on which they criticized Lilienthal was that his machines had inadequate means of control. He had recognized that stable flight meant matching

the center of pressure and the center of gravity. His sole means of recovering from any displacement was by changing the center of gravity. This he did by shifting his own body weight sideways or fore-and-aft as he hung from the glider by his arms. The Wrights noted that both Lilienthal in Germany and Pilcher in England had been killed in their gliders because of inadequate control. They also noted that the control mechanism used by birds was both quicker and more positive than that used by Lilienthal and Pilcher.

When they were ready to move from thought to action, their first action step was on the problem of control. They built a biplane kite with a five foot wing span which could be maneuvered by twisting the wings so as to cause the right and left sides to present different angles to the on-coming wind. This concept was the basis for their original patent (which was tested many times and always upheld by the courts). It is likely that they borowed this idea directly from bird observation, for Wilbur noted in his first letter to Chanute that buzzards regain lateral balance by a torsion of the wings. The design of this kite owed little else to the birds. It had the bridge-type biplane trussed wing originated by Chanute, the famous builder of the Kansas City railroad bridge, and it had the type of wing curvature used by Lilienthal.

They were encouraged enough by the test of the five foot kite that they decided to build a glider big enough to carry one of them and which would be controlled in a similar way. Following suggestions from Chanute's articles they looked for a place with strong surface winds and soft sand to minimize the effects of inevitable crashes. Letters to the weather bureau helped them to locate Kitty Hawk.

As a part of their preparation for this test Wilbur wrote a letter to Chanute. Their purpose in writing to him was to describe their proposed tests and methods, and to secure any sort of comments that he might have. Thus began, on May 13, 1900, a remarkable correspondence between Wilbur and Chanute which was to continue until the latter died in 1910. Both sides of this correspondence have been published (4), and it shows a fascinating sequence in the stages of problem solving.

Chanute seems to have been delighted to discover two articulate and apparently competent young men who were willing to take up the pursuit which his advancing age had caused him to abandon himself. He was always encouraging and quick to recognize progress. He would later on visit them at Kitty Hawk and at Dayton. From the start he provided sources of information which were a result of the world-wide correspondence which he maintained. At one point he sent them a copy, in German, of Lilienthal's book on bird flight, along with translations of some portions which he had acquired from Langley. After reading the material and searching the book, Wilbur was so pleased and so much impressed by the book that he wrote to Chanute telling him that he must have a copy for himself. He said to Chanute, "I have the address of the publisher but I don't know how much the book costs. If you will tell me the price I will order a copy of my own." Chanute wrote back immediately and said, "Please accept my copy as a gift. I have a deposit with the publisher and I will ask him to send me another copy immediately." So the copy which is now in the Archives of Wright State University is likely this one that had been given to the Wright Brothers by Chanute.

On Wilbur's part the letters served to extend to a competent third party the kind of interchange that went on between him and Orville. It is not possible to tell which ideas were Wilbur's and which were Orville's. They were both highly productive and the degree of interaction between them was thorough. But Wilbur was generally the spokesman for two reasons. One of these was that an older brother had some understood prerogatives in their conservative upbringing. The other was that Wilbur wrote much more easily than Orville. They both wrote clearly and well, Orville with somewhat more frequent touches of humor. But writing seems to have been work for Orville. For Wilbur, it seems to have been relaxing. It is easy now to imagine Wilbur, after a long day of building and flying gliders at Kitty Hawk, to relax by sitting down in the evening to write a long letter to Chanute to tell him what they had done and what they were learning by that day's activities.

The correspondence between Wilbur and Chanute contains more than just words

and concepts. As they began their glides and tests, they regularly sent Chanute copies of the records of each flight; how much weight was aboard, the dimensions of the glider, how high the wind was, how far they glided, the slope if any of the ground, and similarly pertinent information. Chanute frequently made his own calculations of lift and drag to match their calculations. These were done to determine the efficiency of the machine they were working with at the time. Chanute was very generous with his time and efforts, and even offered them money to assist with the expenses of the tests. They were happy to have him as an additional calculator and back-up consultant, but always declined the offers of financial aid. Chanute was an encourager, catalyst, participant and suggester. He would double-check their calculations and consider with them the relevance to Lilienthal's and other data. He was in the role of senior advisor, though from the beginning Wilbur and Orville had a position of some technical independence gained by the knowledge provided by their own testing of ideas. By about the end of 1901 their technical self-confidence was great enough that they no longer looked externally for technical aid. Chanute was still senior advisor, but now primarily in matters of publication and professional relations.

When they went to Kitty Hawk for their first large glider tests in 1900, they found a limitation on the length of the lumber they could buy, which limited that glider to a wing span of 17 feet. They rigged it initially with dihedral (high wing tips) for stability, but soon found out that dihedral made the glider nearly uncontrollable in gusts of wind. They straightened out the wings and found their machine easier to control. They built onto this machine what they called a front rudder for fore-and-aft control. We would describe it as an elevator for pitch control, but they did put it in front. They reasoned that the front position would make the glider stable in pitch if the center of pressure changed with angle of attack the way the literature said it did. And, both Lilienthal and Pilcher had tails on their gliders and both had times when pitch went out of control. On their first test they found that with the front rudder their vehicle was unstable in pitch. They reasoned that they would pay the price of instability to have the rudder out where they felt it would give a more positive control action against the nose dive. They were already familiar with descriptions in the

literature of stalls and spins, and they were very conservative in this risky venture. They wanted to take every precaution to make sure that what happened to Lilienthal did not happen to them. As often as they could they even did their gliding quite close to the ground. There are descriptions of glides in which they apparently flew some distance only a foot or so off the ground. They kept that front elevator until 1910, putting up with its instability all that time.

From the calculations of the 1900 tests with the first large glider, they did not get nearly as much lift as they had predicted. They observed also that they measured significantly less drag (they called it drift) than Lilienthal's data led them to expect. They were careful and systematic in their measurements and they knew that the differences were real. They had calculated that the glider should lift its assigned weight in a 20 mile wind at a 3 degree angle of attack. They measured an angle of 20 degrees in a 25 mile wind. After much deliberation they decided that the difference was due to the degree of curvature (front to back) of the wings. They had used a curvature of 1 in 22 and they knew that Lilienthal had used 1 in 12. They would prepare their 1901 tests so they could evaluate the effect of degree of curvature.

For the 1901 tests they built their second large glider to their desired size. It had a 22 foot wing span and a 7 foot chord (front to back). They arranged it so they could vary the degree of curvature of the wing by tightening some wires and loosening others. They set it up first so they would match Lilienthal's wing with a curvature of 1 in 12.

From the standpoint of getting their expected results, the 1901 tests were a disaster. In their first flights they still did not get nearly as much lift as Lilienthal had and they continued to get significantly less drag. Somewhat less perplexing but significantly more frightening, was the fact that the machine was now almost uncontrollable in pitch. They reckoned that the center of pressure was now almost 30 inches back from the leading edge of the wing, and almost full elevator control was required to fly level. This compared to the light pressure which had sufficed in 1900.

They changed the degree of curvature to resemble their 1900 machine and

were able to regain good control. They reshaped the leading edge of the wing and got some improvement in lift and drag. They did an experiment to prove to themselves that the center of pressure did not travel in a uniform direction with changes in angle of attack, and that this reversal occurred within the range of angles they used for gliding.

The end of the 1901 Kitty Hawk tests marked the lowest morale point recorded for Wilbur and Orville. They had proved that their own control system could be made to work, but everything else now seemed to be escaping predictability. The enormity of the problem was clear to them - if they were going to fly they would have to produce by themselves better data than had been produced by all the aerodynamic investigators in the history of aviation! They did not have much hope of being able to do it.

Though they could not now see their way through, Wilbur and Orville continued to follow the implications of their studies. Shortly after Wilbur returned to Dayton from addressing the Western Society of Engineers, he wrote to Chanute on September 26, 1901, "I am arranging to make a positive test of the correctness of the Lilienthal coefficients at from 4 degrees to 7 degrees..." His plan was to put a curved wing model and a flat plate on a freely rotating bicycle wheel, mounted at a defined angle to each other. When the wheel was moved into a steady wind, the two test models would move the wheel until the forces from the models just balanced each other. The desired wind velocity was achieved by mounting the wheel just ahead of the handle bars on a bicycle and riding the bicycle to create a wind.

On October 6, 1901 Wilbur wrote to Chanute,

> "We have made the experiment of balancing a curved surface against a plane surface 66 percent as large, placed normal to the wind, and find that instead of 5 degrees as called for in Lilienthal's table an angle of 18 degrees was required.....
>
> "The advantage of the curve over the plane was so much greater than we had expected.....

"Although the curve was found to be far less effective than Lilienthal's table would indicate, it was so much in excess of the plane that we considered it important to obtain tests of greater exactness at smaller angles....."

He then went on to describe the first wind tunnel they built in their bicycle shop. With that machine they had already produced some additional results:

"We found in other experiments that decreasing the ratio of lateral to longitudinal dimensions was more costly to the plane than to the curve....

"....maximum advantage in lift is obtained with a curvature of about 1 in 9....

"Experiment further confirmed the correctness of Lilienthal's claim that curved surfaces lift at negative angles."

Still within that same letter of October 6 Wilbur tells Chanute that he and Orville have decided to construct a machine for the special purpose of making tables.:

"I think that with it a complete table from 0 degrees to 30 degrees can be made in thirty minutes, and that the results will be true within one percent..."

"I am now absolutely certain that Lilienthal's table is very seriously in error, but that the error is not so great as I had previously estimated."

They proceeded very quickly to build up a very good and accuracte wind tunnel, though it took a whole month to get a straight wind that would vary less than one tenth of a degree. They later described a procedure in which nothing could be moved in the room once a test had begun. Only one operator was allowed in the room and he had to occupy the same position each time.

In another very significant accomplishment they designed and built the instruments which held the models in the wind stream and measured the angles by which the forces balanced each other.

With this very accurate "pressure measuring machine" they quickly explored a

wide range of variables important to aerodynamic design. On November 18, 1901 Chanute wrote:

"It is perfectly marvelous to me how quickly you get results with your testing machine....You are evidently better equipped to test the endless variety of curved surfaces than anybody has ever been."

On November 22 Wilbur wrote to Chanute the following summary:

"Our measuring experiments so far have been merely preliminary, the objects being:

(1) To perfect the methods and instruments

(2) To get a general idea of the effect on pressure and tangential of:

a. Varying the ratio of length to breadth

b. Varying the depth of curvature

c. Varying the position of maximum curvature

d. Sharpening or thickening the front edge

e. Curling the rear edge

f. Rounding or sharpening the ends

g. Superposing the surfaces

We are now engaged in making a large number of models of typical shape and will measure them with the greatest care."

By the time they finished their series of experiments in the winter of 1901 -2 they had accomplished by themselves the kind of knowledge production which only a few months earlier they had despaired would be done in their lifetime. On December 19, 1901 Chanute would write:

"If your method and your machine are reliable you have done a great work, and have advanced knowledge greatly. Your charts carry conviction to my mind

and your descriptions and comments are very clear. I must especially commend the system by which you went about to ascertain the best form of surface, instead of trying haphazard experiments."

By the time the winter was over and the experiments were finished Wilbur and Orville knew how to solve all their remaining problems. No longer would they be surprised when they designed a flying machine and put it in the air. When they designed their 1902 glider and the 1903 flyer they would both perform very close to predictions. Not only were they not surprised on December 17, 1903 when their flyer took to the air, they would have been very surprised if it had failed to do so.

They Evaluate Langley and Lilienthal

There were two famous names which came up for evaluation during this series of experiments. One was Langley. At one point in the experiments Wilbur reported a curiousity about the agreement of their data with those of Duchemin and Langley. He was surprised to note in their own data that the normal pressure on a square plane was greater at 30 to 35 degrees than at 45 to 50 degrees. They constructed a special balance with two squares mounted at 90 degrees to each other. They would not simply balance with each 45 degrees to the wind, but would go to one side or the other. Then Wilbur wrote to Chanute (Dec. 1, 1901):

"On looking up Langley again I notice that on page 23 he draws his line... he omits a very high measurement at 30 degrees. If he had followed his observations, his line would probably have been nearer the truth. I myself have sometimes found it difficult to let lines run where they will, instead of running them where I think they ought to go. My conclusion is that it is safest to follow the observations exactly, and let others do their own correcting if they wish."

They would always praise Langley for using the power of his position to make

aviation respectable, but they were never to speak well of his technical contributions.

The other famous name was Lilienthal. Nearly all writers about the experiences of Wilbur and Orville have reported that they began their wind tunnel experiments because they knew the Lilienthal tables to be in error. That is what Wilbur and Orville wrote as they began their scientific experiments, and that is what they gave in later years as the reason for beginning the experiments. But, on December 1, 1901 Wilbur wrote to Chanute:

> "The Lilienthal tables have risen very much in my estimation since we began our present series of experiments for determining lift.... for a surface as near as possible like that described in his book the table is probably as near to correct as it is possible to make it with the methods he used....
>
> "....instead of contradicting Lilienthal it should emphasize the necessity of considering shape, relative dimensions, and profile in calculating the expected performance of a machine."

Chanute responded immediately:

> "I am very glad that the Lilienthal table has risen in your esteem, both because I feared that I might have led others astray by publishing it, and because it was hard to believe that his glides should not have disclosed to him any serious error."

Just as they did not make public the data from their wind tunnel research, they did not publish the vindication of Lilienthal in that letter of December 1, 1901, which was the result of that research. They stated in later years only that they began the research because they had concluded at Kitty Hawk that Lilienthal was not entirely correct. They always spoke well of him, both in print and in their private notebooks and correspondence. After they had made a business of aviation they sent his widow a gift of $1,000 in recognition of his contributions to solving the problem of manflight.

They Did Not Publish the Data

By November of 1901 Chanute was urging Wilbur to prepare accounts of their wind tunnel experiments for publication. In February 1902 Wilbur told Chanute that, "I think I shall prepare to make them public some time during this summer. We may decide to repeat the experiments with a slightly different apparatus, to make sure that no defect escaped our attention before." But the data were never published by them. After a few years they were to treat this information as a part of the secrets which gave them an edge over their competitors. But in 1902 there was likely another reason. On March 11 of that year Wilbur wrote Chanute that he had "been utterly unable myself to devise a system of formulae which are applicable to both gliding and power machines." It seems quite likely that their tools of algebra and trigonometry finally set some limits to their scientific contributions. There is the suggestion here that in the end they could not put their ideas in a form as finished as they would like, and that was the immediate reason they did not publish the data. In the years after Wilbur died in 1912 Orville repeatedly intended to write the story, but writing did not come easy for Orville.

It is Much Safer on the Ground

As the gloom of August 1901 yielded to the quiet confidence of December 1901, Wilbur and Orville now knew how to build a machine that would fly. But they were painfully aware that they still did not know how to fly. Their 1900 and 1901 gliders had not been very competent flying machines. Their personal flying experiences had been highly useful in helping to analyze the problems of efficient wing design, but neither machine would fly well enough for them to build up the skills they knew they needed. Wilbur had written to Chanute on June 19, 1901 that "I only regret that so few investigators seem to be actively at work trying to gain the knowledge and skill necessary to manage aeroplanes in the air. There is really no other way of solving the problem."

In their first control ventures with the 1900 machine they tied down first the elevator then the wing warping and practiced with only one control at a time. They found the simultaneous use of both of them to be very confusing. As they developed their control skill they began to work with both of them at the same time.

When they built the second glider in 1901 it was larger than any which Chanute had dared to use. Wilbur explained that, "As the weight of the body is not moved in our plan of balancing, we think the large machine will not be much more difficult to control than a smaller one." For the most part he was right in that observation, but large or small they had a lot to learn. An entry in the Chanute-Huffaker diary (4) records an observation of Wilbur at Kitty Hawk on August 9, 1901:

> "A number of excellent glides were made, Mr. Wilbur Wright showing good control....In two instances he made flights curving sharply to the left, still keeping the machine under good control.....
>
> "On the occasion of the last flight made while skimming along about a foot above the ground, the left wing became depressed and in shifting his body to the right to bring it up again (that movement operated the wing warping) he neglected the fore-and-aft control and plunged suddenly into the ground. He was thrown forward into the rudder, breaking a number of the rudder's ribs and bruising his nose and eye."

They had chosen well to do their learning where the sand was soft and would minimize the damage when they crashed. They would receive their share of bruises but no serious injury until a propellor came apart on the day of the first military test in 1908.

Two weeks after the bruised nose and eye venture Wilbur told Chanute that "We proved that our machine does not turn (i.e., circle) toward the lowest wing under all circumstances, a very unlooked for result and one which upsets our theories as to the causes which produce turning." They worked out the solution to that problem

in the air in 1902. Meanwhile Wilbur told the Western Society of Engineers in September of 1901 that he and Orville had confirmed that "Practice is the key to the secret of flying."

Soon after they got to Kitty Hawk with their third large glider in 1902 they knew they were entering the final phase. At last they had a machine that would fly and it was now possible for them to build up their flying skills. And fly they did. Within a few days they were making dozens of flights each day. Soon they learned that the fixed vertical tail they had put on this machine did not, by itself, solve the problem of the machine's not always turning in the direction of the low wing. After suitable discussion they decided to make the rudder double and movable, and while they were at it they coupled rudder and wing warp to make coordinated control with one movement. Later they would decouple them for a greater range of control.

While we have to read between the lines to imagine some of the adventures they must have had with that first capable flying machine, they recorded quite a few in their vivid style. They described as "well digging" the results of stalls and spins that went beyond their rudimentary skills in control. Many times they must have given thanks for the soft sand. They described the tendency of the machine to "pierce the aetherial" when the nose would pitch high and the machine rise up until it "lost headway". There is a good description of this kind of flight with Orville on the machine which finally began to slide backwards. There is an intriguing account of a "tapping" sound in flight which was first reported by Orville. They inspected the machine but could find nothing loose or flapping. A few weeks later it happened to Wilbur,

> ".....the same peculiar tapping began again in the midst of a wind gust. It felt like little waves striking the bottom of a flat bottomed row-boat. While I was wondering what the cause could be, the machine suddenly, but without any noticeable change in its inclination to the horizon, dropped a distance of nearly ten feet, and in the twinkling of an eye was flat on the ground."

These descriptions ring true to those who have themselves followed the Wrights in learning to fly.

The 1902 glider worked so well that they had it in service again in 1903 while they were assembling the flyer with its engines and propellors. On the days of bad weather they did the assembly in their hangar. On days when the weather was good they took "good old number 3" glider out and continued developing their skills. When they finally made that successful test on December 17, 1903, it was flying skill that would close the test. On the fourth and last flight of that day the machine began to pitch up and down and "suddenly darted into the ground", destroying the front rudder. The machine never flew again.

As inexpert as they were on that day they were far and away more knowledgeable than anybody had ever been about what is required to control an aircraft in flight. When the eminent British historian, Gibbs-Smith (5) assesses the efforts of others during the airplane invention years, he uses repeatedly the phrase "chauffer minded". What he meant was that other technical investigators did their book and design work themselves, but when it came time to try out their machines, they had a chauffer at the controls. For Langley's full dress attempt at flight on December 8, 1903, it was his mechanic, Manly, who was aboard. It was probably very fortunate for him that the machine came apart in the first few feet of the flight and dumped him into the Potomac. While his own testimony was that he had thought a good bit about what he would do when certain things happened, he could not have had the slightest chance of being constructive as the pilot. If the machine had got into the air, he would probably not have been among those who celebrated the triumph.

While Manly was being fished from the water, the only two trained pilots in the world were at Kitty Hawk just two weeks from their historic flight. They had got there by becoming competent and methodical engineers, patient and accurate scientists, and finally test pilots. To do all of this in 4.5 years deserves to be ranked among the greatest intellectual achievements in technical history. It is likely that their achievement will be more highly regarded as time goes on. That may be true of Lilienthal, also.

Their Own Retrospection

A few minutes after Wilbur's accident demolished the front elevator of the first flyer, a gust of wind rolled the machine into a ball, completing its destruction. But they were now through for a while with their need for high surface winds and soft sand. Their 1904 and 1905 flyers were flown from Huffman prairie, near Dayton, where they built a hangar. The 1905 machine had enough fuel to fly reasonable distances and it allowed them to reach an adequate level of proficiency. It was the world's first practical airplane.

Their investment in time and money was now appreciable and they now turned their attention to making aviation a business. They were successful in this effort and as a result joined that small group of innovators who became rich from their inventions. When their patent was granted in 1906 they were free to proceed. It was not their intention to become managers or to engage directly in manufacturing themselves. The way they wanted it was stated to Chanute by Wilbur January 10, 1906,

> "If the French deal goes through all right, we will have no difficulty in securing all the money we need without exploiting the invention commercially or assuming any business responsibilities. It will leave us entirely free to pursue a number of scientific studies which we have hitherto carried only far enough to settle practical points."

In the end they had it their way, but it took longer than they had thought. When they had a practical airplane at last in the 1905 machine, they locked it up in the hangar to prevent their ideas from being pirated until they could get adequate licensing agreements worked out. It was to stay in the hangar for two and a half years.

The strain from the delay and negotiations began to have its effect on Chanute. Some of the parties in negotiations were using pressure on him to get the Wrights

to sign with less than their asking conditions. Chanute wrote Wilbur in October 1906 suggesting that they lower their price. Wilbur responded with a discussion of the ins and outs of the negotiating positions and then summarized their position:

> "If it were indeed true that others would be flying within a year or two, there would be reason in selling at any price but we are convinced that no one will be able to develop a practical flyer within five years..."(Oct. 10, 1906).

Wilbur went on to explain that this position was one which they had come to after much calculation,

> "It takes into consideration practical and scientific difficulties whose existence is unknown to all but ourselves. Even you, Mr. Chanute, have little idea how difficult the flying problem really is. When we see men laboring year after year on points we overcame in a few weeks, without ever getting far enough along to meet the worse points beyond, we know that their rivalry and competition are not to be feared for many years.....We do not believe there is one chance in a hundred that anyone will have a machine of the least practical usefulness within five years."

Now Chanute had written in 1894 (2, p. 9) that,

> "Science has been awaiting the great physicist, who, like Galileo or Newton, should bring order out of chaos in aerodynamics, and reduce its many anomalies to the rule of harmonious law."

While Wilbur and Orville did not quite do that, neither has anybody else. In 1976 aerodynamics remains frustratingly empirical. But what they did accomplish was to set in this area a model of procedure which is still followed. In 1939 George Lewis would give them credit (6) for having in 1901 dealt accurately with all but one of the modern variables of aerodynamics. He said that eminent

research scientists in this field have almost universally employed the same method of attack.

But Chanute was not quite ready to give them so much credit. He wrote on October 15, 1906,

> "I cheerfully acknowledge that I have little idea how difficult the flying problem really is and that its solution is beyond my powers, but are you not too cocksure that yours is the only secret worth knowing and that others may not hit upon a solution in less than "many times five years"? It took you much less than that and there are a few (very few) other able inventors in the world."

Wilbur's reply was one which seems to reveal a combination of modesty, confidence, and analytic appraisal of the process:

> "Do you not insist too strongly upon the single point of mental ability? To me it seems that a thousand other factors, each rather insignificant in itself, in the aggregate influence ten times more than mere mental ability of inventiveness. The world does not contain greater men than Maxim, Bell, Edison, Langley, Lilienthal, & Chanute. We are not so foolish as to base our belief (that an independent solution of the problem of flight is not imminent) upon any supposed superiority to these men and to all those who will hereafter take up the problem. If the wheels of time could be turned back six years, it is not at all probable that we would do again what we have done. The one thing that impresses me as remarkable is the shortness of time within which our work was done. It was due to a peculiar combination of circumstances which might never occur again. How do you explain the lapse of more than 50 years between Newcomen and Watt? Was the world wanting in smart men during those years? Surely not! The world was full of Watts, but a thousand and one trifles kept them from undertaking and completing the task." (Oct. 28, 1906).

Wilbur and Orville were modest, but they were also honest. They knew that they had accomplished something great, and that the rest of the world would take a while to catch up. It is the thesis of this paper that it would indeed have taken a while for the rest of the world to catch up, and that the main reason was their method. Wilbur and Orville put together in their own experience that combination of engineering, science, and operational test which has characterized aerospace research and development ever since. It was their method, not their luck, which made them the fathers of powered manned flight.

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